humidity and of evaporation deserve special note. The lack of relationship between the graphs of these two kinds of data is clearly seen and the employment of relative humidity independent of temperature is obviously of little importance in evaporation and transpiration studies.

No attempt will be made at this time to show just why or how this approximate relation holds true or to discuss any evaporation formulas. The present purpose is to present the results of a number of experiments that were carried out with the object of testing this particular relation suggested by Livingston. This paper is mainly intended for the ecologist. A suggestion is given as to how relative humidity and temperature data, together with those of wind velocity, may be used apparently to as good advantage as evaporation data. This should help make a large amount of the valuable data collected by the Weather Bureau more directly useful to his particular needs.

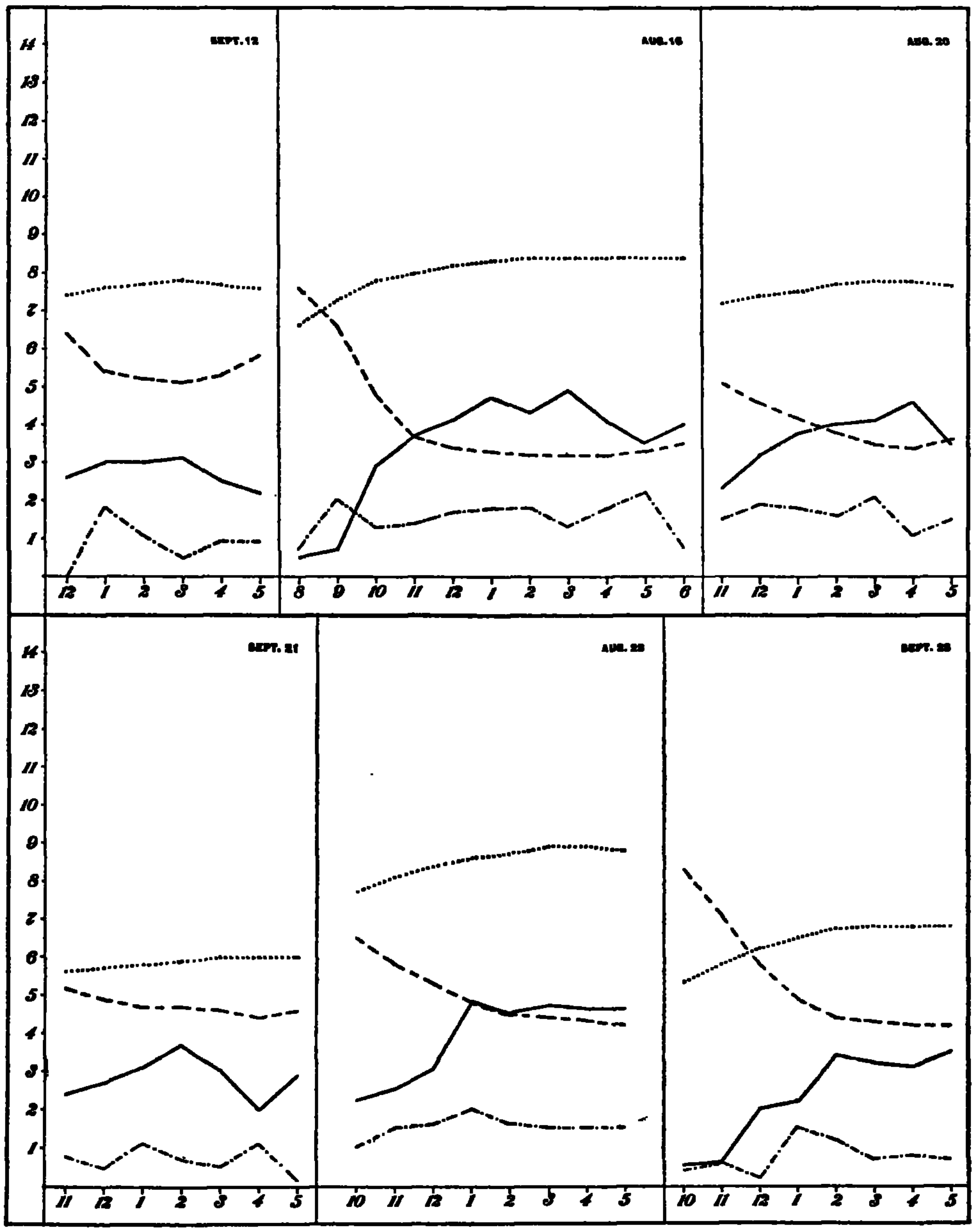

FIG. 2.—Graphs of values representing evaporation from porous-cup atmometers (full lines), air temperature (dotted lines), relative humidity (dash lines), and "radiation" (dash-dot lines).

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INCREASE OF PRECIPITATION WITH ALTITUDE.[1]

By ALFRED J. HENRY, Meteorologist.

[Dated: Weather Bureau, Washington, Jan. 11, 1919.]

Thirty-odd years ago, when the irrigation of arid regions in southwestern United States was first seriously considered, much embarrassment was caused by lack of definite knowledge as to the increase of precipitation with increase of altitude.

For the sake of brevity, the relation between the increase in precipitation in connection with increasing altitude above sea level will be referred to hereafter in this paper as the "precipitation-altitude relation."

In the absence of gage records, various methods have been used to interpolate the rainfall of higher altitudes, the most common one being based on considerations of vegetal cover and topography.

[1] Read before the Association of American Geographers, Baltimore, Md., Dec. 27, 1918.

In recent years an organized effort has been made by the United States Weather Bureau to extend available information as to the depth of precipitation, especially snow, in the higher elevations in the United States, mainly west of the 100th meridian. In various other ways the number of gauge records for elevated stations has increased. Since a more comprehensive knowledge of the subject will be immensely useful and practical, it is proposed to make a brief study of these new records and existing old records in connection with those of the adjoining lowlands and to set forth the results in this paper.

The general law of increase of precipitation with increase of altitude, as stated by Hann, has not been modified by recent studies, but it is now possible to analyze the effect of altitude in a little more detail than was the case 25 years ago.[2]

Hann states[3]—

The cause of the increase of winter precipitation in moderate altitudes is to be sought in the fact that in consequence of topographic features orographic rains, called by Angot "pluies de relief," first increase with increasing altitude, then decrease. There is therefore a level or zone of maximum precipitation above which the increasing frequency of precipitation does not counterbalance the diminution in its intensity. The ascending air masses become continually colder and drier, and their precipitations are therefore always scant. In the greatest altitudes precipitation is in a form of fog or finely pulverized snow.

The altitude of the zone of maximum precipitation depends upon the average condition of saturation of the ascending air masses, their relative humidity, and the temperature at which condensation begins. In winter great relative humidity and low temperature together unite to depress the level of the maximum zone of precipitation; in summer dry air and high temperature elevate it.

It has been my experience that there is more or less confusion in some minds as to the facts above set forth, more particularly as to the existence of a zone of maximum precipitation above which precipitation decreases with increasing altitude. It is rather curious how such confusion should arise, in view of the well-known fact that the greater the elevation the lower the air temperature, and consequently the less the capacity of space at the higher elevations for moisture.

The most favorable conditions for an increase in precipitation with increase in altitude, viz, saturated air and relatively high temperature, are found in the Tropics.

INDIA.

Probably the most familiar illustration is that afforded by the station of Cherrapunji, in the Khasi Hills of Assam. This station is situated on the edge of a plateau overlooking the plains of Sylhet 4,000 feet (1,219 m.) below. Some uncertainty as regards the amount of the true average annual rainfall at the station arose about 25 years ago and has not yet been cleared away. The consensus of opinion, however, is that the true average is close to 500 inches (12,700 mm.) annually instead of 600 (15,240 mm.), as given in many of the earlier publications.

For our purpose it may be placed at 500 inches (12,700 mm.) and the average of the plains below at 100 inches (2,540 mm.). Accordingly, we have an increase of 400 inches in a vertical distance of 4,000 feet, or at the rate of 100 inches per thousand feet (830 mm. per 100 m.). This extraordinary increase must be considered as a purely local phenomenon due largely to the high temperature and moisture content of the air and the abruptness of the slope up which it is forced.

So far as known the natural conditions in no other part of the world are so favorable for a very great increase in the rainfall with increasing altitude, except, perhaps, on the western Ghats and in portions of the Hawaiian Islands.

I quote the following from an abstract of a paper on "The Tata Hydro-electric Power-supply Works, Bombay," by R. B. Joyner, published in *Nature*, London, Nov. 21, 1918, pp. 236–7:

"The monsoon rain on the western Ghats, though always heavy, is very variable in amount. The least annual amount during the last 48 years was 82 inches on the edge of the Deccan plain, and the greatest amount during the past 11 years, in which special gauges have been fixed, on hilltops as well as in plains is 546 inches, which fell in a little more than three months, 460 inches falling in about two months. The minimum fall of 82 inches is very exceptional, and the maximum given may be equally so. * * *

"The amount of 546 inches measured at one hill station in the lakes catchment is not more than has been measured in two or three out of the past 50 odd years at Cherrapunji, in the Assam Hills, which has the heaviest rainfall hitherto known; but there rain falls during seven months of the year, so that the amount measured for this work for that particular year may claim to be the heaviest rainfall ever yet measured.

"The works [to supply Bombay with 100,000 horsepower for 10 or 12 hours a day during about nine months of the year] are probably unique, considering the very heavy rainfall and the very steep rocky slopes, giving the greatest discharge perhaps ever recorded. The catchment area of the two lakes is only 16½ square miles, while of this the full lakes area is about 7½ square miles. * * *

"The water after use is available for irrigation, so valuable in a country without a drop of rain for a large part of the year. [Thus the monsoon rains in three or four months will supply the coast people with water, food, lights, raw materials, power for manufacture, power for making fertilizer, and power for transportation.]"

It is interesting to note the very striking change in the altitude-precipitation relation which takes place in passing from a region of moist air, mostly under cyclonic control, to a region of dry air, mostly under anticyclonic control. The west coast of Africa below latitude 20° South is a case in point. At Port Nolloth, on the coast, latitude 29° 16′ South, the average annual precipitation is but 2.7 inches. At Klipfontein, about 45 miles inland, near the top of the plateau, at an elevation of 3,084 feet, the average is 9 inches, and the rate of increase with increase in altitude is therefore barely 2 inches per thousand feet, (17 mm. per 100 meters), as compared with 100 inches at Cherrapunji. The west coast of South America also affords examples of a very small increase in precipitation with increase in altitude.

JAVA.

Rather recently there has come to hand a Rainfall Atlas of Java.[4] This work contains tables of the monthly and annual precipitation for 1,061 stations in Java, many of the series of observations covering periods from 15 to 33 years in length.

The orographic features of Java in connection with the wind system of the island conspire to produce excellent examples of the influence of topography upon rainfall. The elevated regions of the island are found in the central part, with a general east-west trend. The mountain system is not continuous, but consists rather of a large number of more or less isolated volcanic summits ranging in altitude from 1,000 to 3,000 meters (3,281 to 9,842 feet), only a small number of which exceed 3,000 meters. On the slopes of these summits and the ridges radiating therefrom the streams of the island take their rise, flowing generally directly to sea. The northern coastal plain

[2] Two neighboring places with the same total rainfall may differ considerably in individual months. Thus in Essex, England, Halstead at 139 feet above sea level gets more rain in months with over 50 mm., but less in months with under 25 mm., than does Ridgewell at 269 feet. (F. J. Gurney, M. O. Circ. 13, June 23, 1917, pp. 3-4.)—C. F. B.

[3] Lehrbuch der Meteorologie, 3d edition, Leipzig, 1915.

[4] Results of Rainfall Observations in Java, by Dr. W. Van Bemmelen, Batavia, 1914. B. C. Wallis has written an illuminating discussion of the rainfall of Java in the Scottish Geographical Mag., 1917, 33: 108–119. Maps, diagrs., bibliog. There is also a good illustrated review of this by Prof. Mark Jefferson in Geogr. Rev., New York, June, 1918, 5: 492–495.

is much more extensive than the southern, and the streams are more important, both physically and economically.

There are two rainfall seasons—first, that of the northwest monsoon, October to March; and, second, that of the southeast monsoon, April to October. In April and May the wind is variable; June, July, and August are the months of the settled southeast monsoon. The change to the northwest monsoon usually takes place in October, at times as early as September or as late as November. Although the rainfall of the northwest monsoon is greater than that of the southeast, yet points at sea level on the north coast receive less rainfall than points at sea level on the south coast, especially in the western part of the island. This is probably due to orographic control.

As might be expected, the island presents many exceptions to the general precipitation-altitude relation. Some

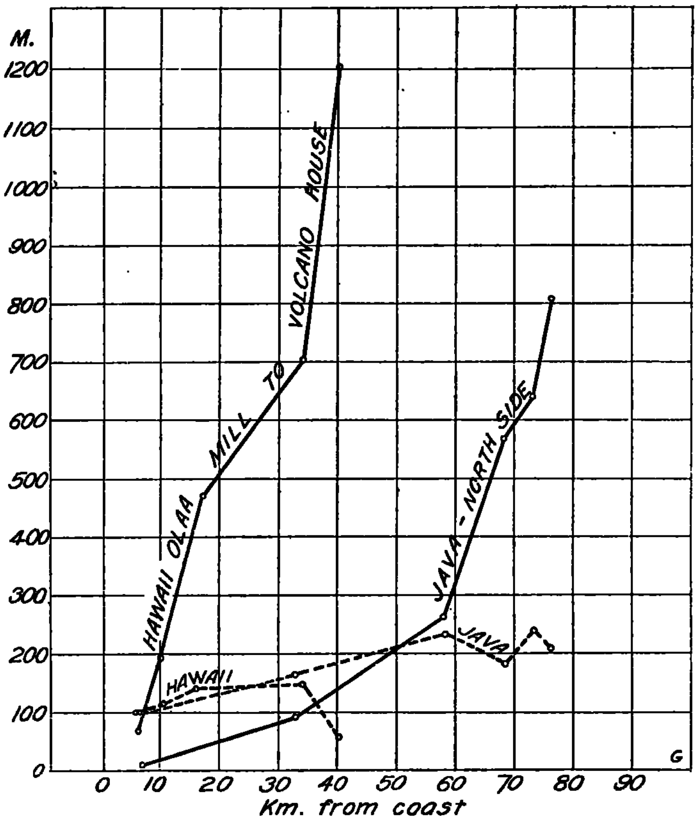

FIG. 1.—Precipitation—altitude relation, Java and Hawaii. Solid lines—Profile of sections. Dashed lines—Relative amount of precipitation in percentages.

of these exceptions will doubtless be better understood upon a fuller disclosure of the details of exposure to the rain winds, and also of the effect of the general relief of the island upon the rainfall.

A cursory examination of the data seems to indicate that the northwest or winter monsoon does not cast a marked rain shadow over the leeward slopes. The rain shadow of the summer monsoon is much better defined.

I have selected from the records in Van Bemmelen's work those which serve to form a rainfall profile across the western portion of the island, beginning with the station Batavia at sea level—annual mean 1,829 mm. (Fig. 1.) Considering that amount as unity, or 100 per cent, I have computed the relative amounts at points with increasing elevation as one passes inland from the coast and approaches the divide. No observations are available for the divide, but I have formed a second profile from the south coast leading inland to as near the divide as the available records permit.

The results are given in Table 1:

TABLE 1.—*Java rain profile, west end.*
North side—beginning at Batavia. See Figure 1.

Stations.	Years of observation.	Altitude.	Precipitation. Average amount.	Precipitation. Relative amount.	Location.
		m.	mm.		
Batavia	33	7	1,829	100	7 kilometers south from north coast.
Depok	33	95	3,214	176	North coast plain.
Bultenzorg	33	266	4,304	235	15 kilometers NNE. Salak (2,210 meters).
Bendoengan	18	568	3,319	182	15 kilometers NW. of Pangerango (3,020 meters).
Pasir Pogor	18	640	4,430	242	5 kilometers NE. of Salak (2,210).
Tapos	18	806	3,798	208	11 kilometers NW. of Pangerango (3,020 meters).
South side—Residency preanger regentschappen.					
Tendjoresmi	11	100	3,000	100	Near the south coast.
Tjipari	12	750	3,788	126	8 kilometers north from south coast.
Pandan Aroem	11	850	4,154	138	4 kilometers south of Kendeng (1,370 meters) and 26 kilometers NNE. from coast.

Another cross section starting in the Province of Pekalongan at the city of the same name at an altitude of 9 meters above sea level and distant therefrom only 2 kilometers, proceeding south-southeast up the slopes of the mountain ridge dominated by two summits, Prahoe (2,565 meters) and Slamak (3,427 meters), gives the relative amounts shown in Table 2:

TABLE 2.—*Java rain profile.*
North side—beginning at Pekalongan, and proceeding south-southeast.

Altitude.	Relative precipitation.	Location.
Sea level	100	At Pekalongan.
160 meters	182	South border of north coast plain.
500 meters	265	6 kilometers NW. Beser (1,585 meters) west slope Sengkarang Valley.
700 meters	291	10 kilometers NE. Prabata (1,572 meters), East Slope Koepang Valley.
720 meters	317	9 kilometers NE. Prabata (1,572 meters), East Slope Koepang Valley.
1,500 meters	266	2 kilometers SSE. Prabata, 5 kilometers N. Ragadjembangan (2,176 meters).

South Side—Residency Banjoemas.

Station.	Altitude.	Precipitation. Mean annual.	Precipitation. Relative amount.	Location.
	m.	mm.		
Tjilatjap	6	3,869	100	On the coast.
Djamboe	21	2,678	69	On the plain of Djatilawang.
Tjilongak	217	4,866	126	14 kilometers SSE. Semboeng (1,463 meters).
Kranggan	311	8,305	215	6 kilometers SSW. Semboeng (1,463 meters).

The observatory station Kranggan, with but seven years' observations, gives the greatest average precipitation in Java. It is situated 45 kilometers from the south coast on the headwaters of two small streams, evidently close to, but to the south of, the main divide between the north and the south drainage, respectively.

The elevation of the station and the adjacent topography do not seem to warrant the expectancy of so great a rainfall. Although heavy rains occur in all months of the year, the season of greatest rain is in the northwest monsoon; the maximum falls in October, 1,200 mm.

(47.2 in.), and the minimum in June, 322 mm. (12.1 in.). The presence of Semboeng, 5 kilometers NNE., does not shed any light upon the cause of the very heavy precipitation. The station Djelegong, also on the southern slope, altitude 747 meters (2,451 feet), about 30 kilometers ENE. of Kranggan, and 13 kilometers east of Slamet, 3,427 m. (11,243 feet), has an annual mean precipitation of 6,089 mm. (239.72 in.). The minimum at this station falls in July and August when the southeast monsoon is at its height. The maximum falls in January and December, thus indicating that the northwest monsoon does not cast a well defined rain shadow to leeward.

I have computed the average annual precipitation for six residencies in Java, in zones of increasing altitude beginning at sea level. The altitude intervals are as follows: 0–100 meters, 101–200 meters, 201–300 meters, 301–500 meters, 501–750 meters, 751–1,000 meters. 1,000 + meters.

When the number of stations in any zone is small—less than 6—the minimum weight should be given the averages; for example, under Residency Pekalongan, zone 1,000 + meters, appears the average 5,061 mm. (199.2 in.). This value was computed from the records of but two stations, one of them had an average of 3,591 mm. and the other 6,531 mm., combined mean 5,061 mm. as given. In this case both stations were at practically the same elevation, but one of them was favorably situated to receive heavy rains during the northwest monsoon, while the other was less favorably situated.

In general, there is an increase from sea level inland up to the highest points for which observations are available. As might be expected, there are many exceptions to the general rule which must be explained on the ground of local environment and exposure to the rain winds. Table 3 summaries the results.

TABLE 3.—*Increase of precipitation with altitude, Java.*

NORTH SIDE.

	Residency Batavia.			Residency Pekalongan.			Residency Semarang.		
Altitudes in meters.	Number of stations.	Average. Altitude.	Average. Annual precipitation.	Number of stations.	Averages. Altitude.	Averages. Annual precipitation.	Number of stations.	Average. Altitude.	Average. Annual precipitation.
		M.	*Mm.*		*M.*	*Mm.*		*M.*	*Mm.*
0-100	27	31	2,001	60	27	2,474	68	21	2,426
101-200	4	154	3,326	11	134	3,094	3	154	3,524
201-300	5	235	3,530	8	265	4,062	3	266	2,[illegible]82
301-500	4	432	3,551	10	399	4,363	12	426	3,059
501-750	13	606	3,919	8	628	5,012	11	606	3,372
751-1,000	4	839	4,364	7	841	5,121	6	813	3,604
1,000+	3	1,087	4,593	2	1,516	5,061	4	1,083	4,189

SOUTH SIDE.

	Residency Preanger Regentschappen.			Residency Banjoemas.			Residency Kediri.		
Altitudes in meters.	Number of stations.	Average. Altitude.	Average. Annual precipitation.	Number of stations.	Average. Altitude.	Average. Annual precipitation.	Number of stations.	Average. Altitude.	Average. Annual precipitation.
		M	*Mm.*		*M.*	*Mm.*		*M.*	*Mm.*
0-100	7	21	3,205	15	30	3,229	29	77	1,836
101-200	3	134	3,811	5	148	4,263	12	142	1,855
201-300	6	269	2,923	3	248	4,347	7	251	2,422
301-500	11	400	3,552	1	311	8,305	7	381	2,581
501-750	24	632	2,879	1	747	6,089	7	591	3,437
751-1,000	22	831	3,399	1	956	4,682	2	757	3,918
1,000+	29	1,366	3,392	4	1,082	4,542	2	1,102	5,790

The compilation in Table 3 shows that the average rate of increase on the north side up to 400 meters (1,312 feet) is 333 mm. per 100 meters, or at the rate of 40 inches per 1,000 feet. The rate diminishes to the eastward of Batavia, and is also smaller on the south coast except when the phenomenal record of Kranggan is used.

Two of the south side residencies show a high average for coast stations, while the third—Kediri—shows the opposite.

The altitude of the zone of maximum precipitation on the north side of the island is not far from 1,000 meters (3,281 feet). On the south side it seems to be lower, although the data are not conclusive. In the Preanger Residency a large number of records for elevations 500 to 1,000 meters are available. These records show a considerable decrease in precipitation from an average altitude of 400 meters (1,312 feet) to an average of 632 meters (2,073 feet), and the decrease is continued up to the average level of 1,366 meters (4,482 feet)—the zone of highest average level for which observations are available.

HAWAII.

The rainfall of the Hawaiian Islands belongs to a simple type, being due mostly to the forced ascent of the northeast trades by the mountains they encounter. Usually, therefore, heavy rains fall on the windward slopes and very little rain on the leeward slopes. This condition, however, is reversed during the prevalence of the so-called Kona storms. The name "Kona" in Hawaiian signifies the southwest side or slope, and because these storms are associated with southwest winds and heavy rain on the Kona side of the islands the name Kona has cme to represent a storm with southerly wind and rain.

These storms seem to be merely the trough of a cyclonic depression whose center moves eastward north of the islands and is preceded by southeast shifting to south and southwest winds, and sometimes tremendous rains not only on the slopes, but also on the lowlands. The trough moves slowly occupying two or three days in passing across the group. They are of infrequent occurrence, as might be inferred when it is considered that the barometric gradients associated with them must be of sufficient strength to overcome the northeast trades and produce a wind from the opposite quarter. One or two well-developed Kona storms, however, affect the rainfall of the island very materially, since more rain may fall in a single storm than usually falls in a year, especially on the southwest slopes. Very striking contrasts are thus afforded in the annual precipitation of a series of years.

In considering the precipitation-altitude relation in the Hawaiian group, I have chosen but two examples, the first on the island of Oahu and the second on Hawaii.

There are two mountain systems on Oahu, viz, the Koolau Range in the northeast, extending the full length of the island, the crest being approximately 3.6 miles (6 km.) inland. The Waianae Range extends along the southwest side parallel to the Koolau Range. A cross section across the Koolau Mountains in the vicinity of Honolulu is easily constructed. (See fig. 1.)

Beginning at Waimanola, at sea level, with an annual average of 41 inches (1,041 mm.) considered as unity, the following relative amounts are obtained:

Waimanalo, 25 feet	100
Tantalus Peak:	
1,665 feet	410
1,360 feet	250
Kaliula Peak, 1,200 feet	220
Honolulu (W. B.), 99 feet	60
Honolulu naval station, 6 feet	50

The distance in an air line from sea level at Waimanolo across the range to sea level at Honolulu is about 12 miles (19 km).

Tantalus Peak and Kaliula are on the leeward slope but near the crest.

The rainfall on Tantalus Peak at an altitude of 1,665 feet (507 meters) is four times as great as at sea level about 6 miles (10 km.) distant, practically the same relation that holds at Cherrapunji. Descending on the lee side of the mountains the rainfall rapidly diminishes to about half of the value it has at sea level on the windward side of the range.

The rainfall at Makapuu Point, the extreme southeastern tip of the island, although the measurements are made at an elevation of 570 feet (174 meters) above sea level amounts to only 15 inches per annum on the average. This is explained by the fact that there is no mountain background for that part of the island.

The second chain of stations has been taken from the records of the Island of Hawaii. This island, it will be remembered, contains the two great mountain masses, Mauna Kea and Mauna Loa, altitudes of 13,805 and 13,675 feet (4,208 and 4,168 meters) respectively. Rainfall measurements have been made on the southeast slope of the former at an altitude of 6,450 feet (1,966 meters) and the record covers a period of a little more than 6 years. As compared with the record at sea level at Hilo less rain falls at the elevation above mentioned than at sea level and this fact is confirmed by the records of the chain of stations a little to the south extending from Olaa Mill, north latitude 19° 39′, 4 miles from the coast, to Volcano House, about 25 miles (40 km.) inland, at an altitude of 3,984 feet (1,214 meters). The geographical coordinates of the stations and the relative amounts of rainfall on the average of about 15 years record, except for the station Glenwood, for which but a single year is available, will be found in the statements below:

	North latitude.	West longitude.	Elevation.	Remarks.
	° ′	° ′	*Feet.*	
Olaa Mill	19 39	155 0	210	4 miles from ocean.
Kurtistown	19 37	155 2	640	7 miles from ocean.
Olaa (17 miles)	19 35	155 3	1,530	11 miles from ocean.
Glenwood	19 26	155 10	2,300	21 miles from ocean.
Volcano House	19 26	155 16	3,984	25 miles from ocean.

Considering Olaa Mill average annual precipitation 148 inches (3,759 mm.) as unity, the relative annual amounts up to an altitude of 3,984 feet (1,214 meters) are as follows:

Olaa Mill	100
Kurtistown	115
Olaa (17 miles)	140
Glenwood	145
Volcano House	59

The zone of maximum precipitation in this cross section is below 1,000 meters (3,281 feet) and in general is at a low elevation elsewhere in Hawaii. The precipitation at a point on the southeastern slope of Mauna Kea at an altitude of 6,450 feet (1,966 meters), before referred to, is but 67 per cent of that at Hilo at sea level. A second high level station at practically the same altitude but slightly farther west on the divide between Mauna Kea and Mauna Loa gives a still smaller percentage, viz, 23, of that at Hilo. The zone of maximum precipitation appears to be between 350 and 400 meters (1,148 and 1,312 feet), so far as can be determined from existing records, although more extended observations will probably place it slightly below 1,000 meters.[5]

An eleven-year record at Hakalau (Mauka) 1,200 fee (365 meters) gives an annual average of 280 inches (7,112 mm.) as compared with 142 inches at Hilo.

The southwest slope of Hawaii as represented by the station at Hilea about 2 miles from the coast and at an elevation of 310 feet (95 meters) affords an interesting example of the influence of southwest storms on the rainfall. In 1915 the rainfall of the nine months January to September was 19.12 inches (483 mm.). In November of the same year, due to the prevalence of Kona storms, the rainfall was 20.46 inches (509 mm.) and in December 13.31 inches (338 mm.). Again in 1916, 15.98 inches (406 mm.) fell in January as against 0.10 inch (2.5 mm.) in the same month of the previous year. Nine inches (229 mm.) of rain fell in two days, due to the prevalence of a Kona storm.

There has recently come to notice an account of a rainfall record kept on the summit of Mount Waialeale, elevation 5,075 feet (1,546 meters), Island of Kauai, Territory of Hawaii (Science, Nov. 23, 1917).

The mean of 5 years' observations at this place gives an annual average of 518.4 inches (13,157 mm.), a larger amount than has been recorded elsewhere in the Hawaiian group. Mount Waialeale is the highest point on the island and is situated very near its geographic center. On the windward side there are not sufficient observations to determine the increase in precipitation per thousand feet, but it must be much greater than that found in other islands of the group. A station near the windward coast, Kilauea, elevation 342 feet (104 meters), has an annual average of 69.28 inches (1,758 mm.), an amount considerably less than is found at sea level on Hawaii. If further years of observation should sustain the high average maintained during the five years 1912–1916, Mt. Waialeale will doubtless take rank as one of the rainiest places on the globe. The conclusion as to the height of the zone of maximum precipitation on Hawaii evidently does not apply to the Island of Kauai.

WEST INDIAN REGION.

Jamaica.—The Blue Mountains lie athwart the northeast trades and should afford good examples of the increase of precipitation with increase of elevation. The rainfall régime of the island is by no means simple, there being two distinct maxima, one in May and June, the other in October.

Tropical disturbances which may visit the island in the period July to November are almost invariably attended by very great rainfall, hence the occurrence of a tropical storm in any one of the above-named months has the effect of changing the month of maximum rainfall to the month in which the tropical storm occurred. Shallow cyclonic depressions in the winter months are also attended by heavy downpours of rain.

The heaviest rainfalls on the northeast coast and the average for that part of the island is, in round numbers, 125 inches (3,115 mm.). Passing inland toward the Blue Mountain Range an average fall of 227 inches (5,766 mm.) is found not far from the coast at an altitude of 600 feet (183 m.). Still farther inland the measurements made at Blue Mountain Peak, altitude 7,423 feet (2,262 meters), give 175 inches (4,445 mm.) as the average, an increase of

[5] Martin and Pierce in Water Supply Paper 318, p. 462, place the elevation of the zone of maximum precipitation on Hawaii at about 2,500 feet (762 m.).

but 50 inches (1,270 mm.) in a vertical distance of slightly more than 7,000 feet (2,134 meters).

Porto Rico.—The rainfall régime of Porto Rico is much the same as that of Jamaica. The rainfall is heaviest on the eastern slope of the Luquillo Mountains in the extreme northeastern part of the island. From an annual average of 54.81 inches (1,392 mm.) on Vieques Island, off the northeast coast, the amount increases to 136 inches (3,454 mm.) at Luquillo, altitude 1,200 feet (366 meters), an increase of 82 inches (2,083 mm.); in 1,155 feet (351 meters).[6]

THE UNITED STATES.

Hitherto I have considered examples drawn from tropical or subtropical regions. Let us now consider examples from temperate latitudes, as the Pacific coast and Rocky Mountain States. The conditions under which the precipitation of atmospheric moisture occurs in this region are different from those which obtain in the trade-wind zones and the Tropics hitherto considered. The weather controls in temperate latitudes are almost exclusively cyclonic. It so happens that one of the chief centers of cyclonic origin in the Northern Hemisphere lies to the northwest of the Pacific coast States, and that during the cold season cyclonic control of the weather, especially in western Washington and western Oregon, and to a less extent along the northwestern coast of California, is practically continuous. There is, therefore, superposed upon the ascensional movement of the air due to the mountain systems which parallel in a general way the direction of the coast, an additional small vertical movement due to the cyclonic influence. Hence it is not surprising that the region of greatest rainfall in the United States is found on the Pacific coast.

Hitherto the data submitted have shown a progressive increase in the absolute amount of precipitation from sea level inland as higher elevations were reached. This rule must now be reversed, since the absolute amount of precipitation diminishes with distance from the ocean or other large body of water. Other things being equal, the heaviest precipitation in the United States should be found on the west slope of the Olympics of Washington and the coast range of California and Oregon; but other things are not equal, and, moreover, the absence of rainfall observations in the wettest localities in those ranges makes it impossible to confirm this belief by actual gage records.

The average annual precipitation on Tatoosh Island—a rock which stands 57 to 100 feet (17 to 30 meters) above the ocean level at the mouth of the Strait of San Juan de Fuca—is 88.78 inches (2,255 mm.). At Neah Bay, 7 miles east of Tatoosh Island, on the south shore of the Strait, the average annual precipitation is 108.31 inches (2,751 mm.). The heaviest precipitation of Washington is undoubtedly on the west slope of the Olympic Mountains, which occupy the greater part of the peninsula between the Pacific and Puget Sound. This mountain country is rugged, uninhabited, and measurements of precipitation on the mountain slopes are not available. In the absence of the definite measurements west of Puget Sound I was compelled to determine the rainfall profile as it crossed the Cascades and descended into the arid region of the Columbia River Valley. Three railroad lines cross the Cascades, each of them in a tunnel about 1,000 feet (305 meters) below the summit of the range. I have used the crossing of the Chicago, Milwaukee & Puget Sound Railway at Snoqualmie Pass and, in general, the line of stations following the Northern Pacific westward to Seattle and eastward into the valley of the Yakima and finally into the Columbia River Valley at Kennewick, Wash. The record of but a single year, 1916, has been used. The geographical coordinates of the stations and the relative amounts of precipitation, Seattle annual being considered as unity, appear in the table below.

	North latitude.		West longitude.		Elevation.	Precipitation.	
						1916	Relative amounts.
	°	′	°	′	*Feet.*	*Inches.*	
Seattle	47	38	122	20	209	34.61	100
Snoqualmie Falls	47	30	120	55	667	57.84	167
Cedar Lake	47	25	121	45	1,590	113.25	327
Snoqu lmie Pass	47	25	121	25	3,010	96.48	280
Lake Keechelus	47	19	121	20	2,479	70.16	203
Lake Clealum	47	14	121	4	2,160	27.09	78
Ellenburg	46	59	120	32	1,577	10.27	30
North Yakima	46	36	120	30	1,076	7.22	21
Sunnyside	46	20	120	00	740	7.21	21
Kennewick	46	26	119	15	370	12.04	35

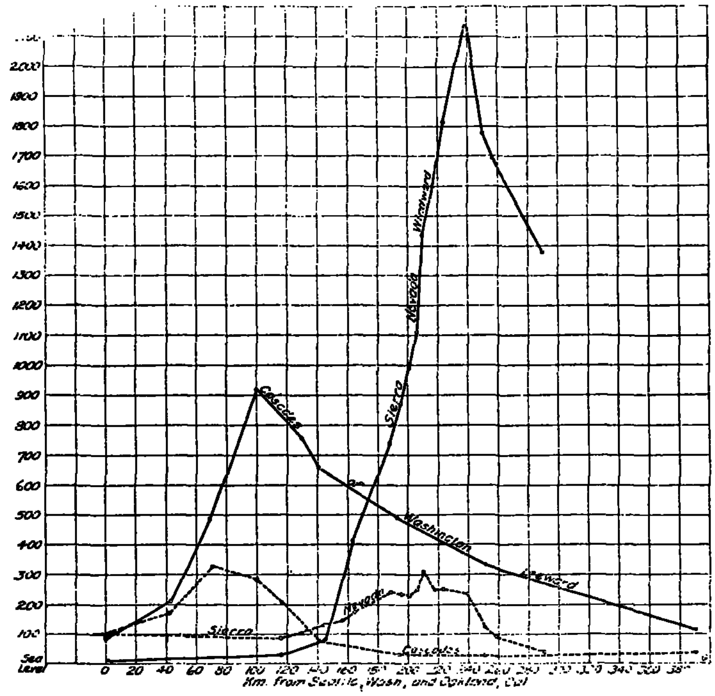

FIG. 2.—Precipitation—altitude relation, Western United States. Solid lines—Profiles of sections. Dashed lines—Relative amount of precipitation in percentages.

The zone of maximum precipitation in Washington and in many other parts of the world is at some distance to the windward of the mountains, as was pointed out by Hill for India many years ago. From the level at Snoqualmie Pass to Lake Clealum, where the rainfall begins to diminish sharply, the distance is 27 miles (43 km.). The diminution of precipitation on the leeward side of the Cascades of Washington does not appear to be so sharp as on the lee side of the Sierra Nevada in central California. The crest of the range at Snoqualmie Pass is 1,000 feet (305 meters) above the rainfall station. (See fig. 2.)

In Oregon the physiographic features are much the same as in Washington, although the mountains of the coast range do not reach the altitudes of the Olympics of Washington and no railway crosses the Cascades; hence a chain of stations crossing the mountains is not avail-

[6] Dr. O. L. Fassig in MONTHLY WEATHER REVIEW, 1909, 37: 982-986.

able. I have assembled, however, the data for the construction of a profile of the annual precipitation beginning at Tillamook, on the bay of the same name, ascending the coast range, thence descending into the Willamette Valley, and thence ascending to Government Camp, a station on the south slope of Mount Hood at an elevation of 3,897 feet (1,188 m.). The cross section is incomplete, but the best available. The geographical coordinates of the stations and the relative amounts of annual precipitation appear in the table below. Average values are used. Tillamook, with an annual average of 102 inches (2,591 mm.), considered as unity.

Stations.	North latitude.	West longitude.	Elevation.	Precipitation.	
				Average.	Relative amounts.
	° ′	° ′	Feet.	Inches.	
Tillamook	45 27	123 51	20	102.0	100
Glenora	45 20	123 50	575	130 0	120
Forest Grove	45 21	123 5	220	51.0	50
Portland	45 32	122 41	75	44.5	44
Headworks	45 27	122 12	719	79.0	77
Welches	45 20	121 57	1,385	82.0	80
Government camp	45 18	121 51	3,890	86.0	84

California.—A very common example of the increase of precipitation with increase of altitude is afforded by the chain of stations along and near the Southern Pacific Railroad from Oakland, Cal., across the Sierra Nevada, descending thence to the dry region of the Great Interior Basin in Nevada and Utah.

Ten-year means have been computed for a chain of stations beginning at Oakland, Cal., and ending at Reno, Nev., and the results are given in the table below, and also appear in fig. 2. Oakland, the base station, is at sea level directly across the bay from San Francisco. The average annual precipitation is 24.30 inches (617 mm.).

Stations.	Elevation.	Relative amounts.	Stations.	Elevation.	Relative amounts.
	Feet.			Feet.	
Oakland	36	100	Towle	3,612	241
Sacramento	71	80	Blue Canon	4,695	304
Rocklin	249	121	Emigrant Gap	5,230	243
New Castle	956	140	Cisco	5,939	244
Auburn	1,363	165	Summit	7,017	223
Colfax	2,421	237	Truckee	5,820	118
Iowa Hill	2,825	229	Boca	5,531	83
Gold Run	3,222	226	Reno (Nev.)	4,484	35

Alexander McAdie shows that the average rate of increase on the west slope up to 1,500 meters is about 75 mm. per 100 meters; and from the summit down the east slope the decrease is 147 mm. per 100 meters of descent.[7]

According to the above table, the zone of maximum precipitation in the Sierra Nevada is somewhere near 1,500 meters (4,921 feet). The fact that it varies in altitude with different storms was brought to the writer's attention by an examination of the records of two heavy rainstorms in southern California in January, 1914, and 1916, respectively.

It may easily happen that the air in one storm is nearer to saturation than in another and this is probably the explanation of the difference in the relative amounts in the two storms. A second example of the precipitation altitude relation in California, consisting of but four stations, beginning at Fresno in the Great Valley of California and ascending the mountains near that place, follows:

	Altitude.	Precipitation (mean of 2 seasons).	Relative amounts.
	Feet.		
No. 1	230	11.40	100
No. 2	1,013	31.53	277
No. 3	2,441	31.63	278
No. 4	3,500	50.16	440

This group of stations is about 180 miles (290 km.) south of the Union Pacific group and in a region of less rainfall. The increase in precipitation on the west slope of the Sierra Nevada from the floor of the Great Valley to the 5,000-foot (1,524-meter) contour, according to Chas. H. Lee, is 8.5 inches per thousand feet (70 mm. per 100 m).[8] A. McAdie[9] shows that in southern California where the zone of maximum rainfall is much higher, the precipitation increases about 50 mm. per 100 meters (6 in. per 100 ft.) up to 2,500 meters.

The rate of increase of precipitation with increasing elevation is not so well marked east of the Sierra Nevada and the Cascade Ranges, but is still a characteristic of the high-level climate between the ranges above named and the Rocky Mountains.

Idaho.—The elevated regions of Idaho are in the eastern part of the State, particularly along the Montana-Idaho boundary. There is also a central plateau region whose general elevation slightly exceeds 5,000 feet (1,524 meters), with mountain ranges and isolated peaks considerably higher. The precipitation of this central plateau region and also of the southeastern plateau is light regardless of its altitude. While no measurements have been made in the mountain slopes, the central plateau records maintained at points between 5,000 (1,524 meters) and 7,000 feet (2,134 meters) elevation generally indicate an annual rainfall of less than 20 inches (508 mm.). The region of maximum precipitation, 35 to 45 inches (889 to 1,143 mm.) annually, is found on the western slopes of the Cabinet and Coeur d'Alene Ranges and probably also on the western slope of the Bitter Root Range. I am able to present the records of four stations beginning at Coeur d'Alene at the north end of the lake of the same name and extending to the village of Burke, 50 miles (80 km.) east-northeast of Coeur d'Alene and about 2,000 feet (610 meters) higher. The details of the stations appear in the table below:

Stations.	North latitude.	West longitude.	Elevation.	Precipitation.	
				1916	Relative amounts.
	° ′	° ′	Feet.	Inches.	
Coeur d'Alene	47 41	116 47	2,157	28.23	100
Kellogg	47 33	116 0	2,330	37.20	132
Wallace	47 25	115 55	2,728	47.26	170
Burke	47 32	115 47	4,082	46.20	164

These records, for 1916 only, show that with an increase in elevation of 1,925 feet (585 meters) there is an increase of 18.03 inches (458 mm.) in the annual precipitation. This increase corresponds roughly to an increase of 9.4 inches per thousand feet, or, in metric measures, 78 mm. in 100 meters.

The region here considered—the northern part of the State—has a fairly effective mountain background in the Cabinet and Coeur d'Alene ranges whose summits scarcely exceed 6,000 feet in altitude although individual peaks may be higher. This region is, moreover, in the

[7] Alexander McAdie, "The rainfall of California," Univ. Calif. Geogr. Pub., 1914. I:127-240, pls. 21-28. (Review, Science, 1914, n. s. vol. 40, pp. 29-30.)

[8] MONTHLY WEATHER REVIEW, 1911, 39: 1099.
[9] Loc. cit.

direct path of traveling cyclones which move inland from the Pacific and is, therefore, more favorably situated to receive generous precipitation than the regions farther to the southward.

A second line of stations leading from the Snake River Valley at Lewiston, altitude 757 feet (231 meters) in a southeasterly direction to the rolling country in Lewis County at general elevation of about 3,000 feet (914 meters) was made by using the records of the following named stations.

Station.	North latitude	West longitude.	Elevation.	Precipitation, 1916.
	° ′	° ′	*Feet.*	*Inches.*
Lewiston	46 25	117 02	757	17.49
Culdesac	46 23	116 42	1,520	20.62
Nezperce	46 13	116 19	3,082	23.45

The above records show that with an increase in altitude of 2,325 feet (709 meters) in a horizontal distance of about 40 miles (64 km.) precipitation for the single year of 1916 increased roughly 6 inches (152 mm.), or at the rate of 2.6 inches per 1,000 feet (22 mm. per 100 meters).

Utah and Colorado.—There is an increase in precipitation with increase of altitude on the southwest slope of the Wasatch Mountains, but sufficient data are not available to show definite results. At the Utah Experiment Station, maintained by the Forest Service in cooperation with the Weather Bureau, observations for two seasons June to September, inclusive, at altitudes between 8,000 and 10,000 feet (2,438 and 3,048 meters) show an increase of approximately an inch per thousand feet (8 mm. per 100 meters). The rainfall of 1915 at 10,000 feet (3,048 meters) elevation was, however, only 60 per cent of that of the previous year. It is interesting to note that stations at the foot of the Wasatch, elevation about 5,000 feet (1,524 meters), showed the same disparity between the rainfall of the years 1914 and 1915, the latter being exactly 60 per cent of the former on the average of four stations, thus showing a variation in the same sense at both low and high-level stations.

The precipitation observations at Wagon Wheel Gap Experiment Station, maintained by the two services above mentioned, afford information of great interest for a section of marked contrast in topography far removed from the ultimate source of moisture. At this station, detailed measurements of precipitation are made on the eastern slope of a mountain mass which rises from an elevation of about 8,400 feet (2,560 meters) in the valley of the Rio Grande to a little more than 11,000 feet (3,353 m.) at the top of the experimental area.

Records of precipitation are now available for a seven-year period at points which, for convenience, may be designated as follows:

	Altitude.	Average annual precipitation.
	Feet.	*Inches.*
No. 1	9,601	21.12
No. 2	9,609	20.31
No. 3	9,426	20.88
No. 4	9,434	20.24
No. 5	10,949	24.76
No. 6	[1] 11,200	25.59
No. 7	[1] 11,200	25.50
No. 8	[1] 11,500	26.64

[1] Approximate only.

Combining the stations in two groups, an upper and a lower, it is found that there is, roughly, an increase of approximately 3.3 inches per 1,000 feet (28 mm. per 100 m.).

East of the Rocky Mountains.—The highest point in the United States east of the Rocky Mountains is Mount Mitchell, N. C. Fortunately for our purpose, eight months, rainfall observations on the top of that mountain are available. The rain winds of North Carolina are mostly easterly and southerly. But at times they may be from any quarter. The mountain system of which Mount Mitchell is a part trends in a general northeast-southwest direction; consequently the full effect of the rain winds is experienced only when they are from the southeast. The labor of classifying the rainfall according to the direction of the wind is scarcely warranted by the probable value of the results. I have, therefore, used the full eight months' period during which the precipitation was measured on Mount Mitchell and compared the total amount with the totals for the corresponding period at lower levels. The results are set forth in the table below. The cross section is made from Hatteras on the coast to Mount Mitchell in an almost due east-west line, departing north or south therefrom only slightly when necessary to include a connecting station. The last-named station in the table is not a part of the cross section but is added because it is representative of a region of heavy rainfall with southeast winds. The station at Hot Springs, Tenn., is representative of the region to the northwest of the mountains and in their rain shadow. Newport and Knoxville, Tenn., are both west of Mount Mitchell and should show an increase in precipitation with southwest winds. Both stations have slightly greater rainfall than was recorded at sea level in about the same latitude. The mountain effect at points west of Mount Mitchell is apparently very small.

Stations.	North latitude.	West longitude.	Elevation.	Precipitation.	
				Total.	Relative amounts.
	° ′	° ′	*Feet.*	*Inches.*	
Hatteras	35 15	75 40	37	35.70	100
Greenville	35 37	77 22	75	29.92	84
Raleigh	35 45	78 37	390	33.76	95
Ramseur	35 45	79 39	442	34.01	95
Salisbury	35 40	80 28	764	47.95	134
Statesville	35 47	81 53	950	54.89	154
Morganton	35 45	81 41	1,135	47.29	132
Marion	35 41	82 1	1,425	51.86	145
Mount Mitchell	35 43	82 18	6,711	81.90	230
Newport, Tenn	35 58	83 12	1,110	36.62	103
Knoxville, Tenn	35 56	83 58	997	36.53	102
Hot Springs, Tenn	35 53	82 49	1,326	31.74	[1] 89
Rock House, N. C	35 0	83 10	3,000	90.27	[2] 253

[1] Western foothills. [2] About 80 miles southwest of Mount Mitchell.

SUMMARY.

The main features of the precipitation-altitude relation are essentially as follows:

1. The trend of the mountains must be in such a direction as to cause an ascent of the air masses which encounter them. Mountain systems whose axes are parallel, or nearly so, with the direction of the rain winds cause little or no increase in precipitation.

2. The inclination of the slope of the mountain is of great importance; the steeper the slope, other things being equal, the greater the precipitation. The quantity of rain or snow which falls anywhere is also conditioned upon the initial temperature and relative humidity of the air at the beginning of the ascent. Obviously, it also depends, in no small degree, upon the duration of

the winds from the rain quarter, or, in other words, upon the rate of movement of the atmospheric disturbance with which the rain winds are associated.

3. The altitude of the zone of maximum precipitation appears to vary slightly with latitude, being lowest in the Tropics—a little less than 1,000 meters—and highest in temperate latitudes, say, between 1,400 meters and 1,500 meters. It has also a seasonal variation, being highest in summer and lowest in winter.[10]

ALTITUDE RELATIONS OF RAINFALL IN FRANCE.

By E. MATHIAS.

[*Abstract:* "La pluie en France, etc." C. R. Paris Acad., 1919, 168: 105-108; 239-242.]

The precipitation-altitude relation in France may be expressed closely with the formula, $R=R_1+kA-k'A^2$, in which R represents the rainfall in millimeters at altitude A (in meters), R_1 the rainfall at a lowland station, k the coefficient of increase with altitude, and $k'A^2$ a term to take care of the decrease of rainfall above a certain elevation. For the Puy du Dome, and probably for the rest of France, k' is 1/20,000; thus, the formula becomes, $R=R_1+kA-\frac{1}{2}(A/100)^2$. On a map of France the author shows the values of k for each Department. k varies uniformly with latitude, ranging from 0.5 in the Pyrenees (lat. 43°) to 1.2 in the north (lat. 50°).—C. F. B.

THE CONSERVANCY WEATHER AND FLOOD WARNING SERVICE.

[From The Miami Conservancy Bulletin, Dayton, Ohio., Jan., 1919, vol. 1, No. 6, pp. 93-94.]

During the construction of the flood-prevention works it is of vital necessity that the District be informed as much in advance as possible of even slight flood stages in the river. There is much construction equipment, such as drag lines, railway tracks, locomotives, pumps, and motors, which must be used in or near the river bottoms, and failure to protect it from floods would mean very serious loss and delays. It also is desirable that the people of the valley receive all possible advance notice of any floods that may occur before the flood prevention works are completed, so that they may not again be taken unawares as in 1898 or 1913.

Perceiving the necessity of this, the Conservancy District in 1913 established a flood-warning service, under the direction of Mr. Ivan E. Houk. At that time there were only 15 stations in the Miami watershed where accurate measures of rainfall were made, and only three where careful measures of the river stages were made. Steps were at once taken, in cooperation with the United States Weather Bureau, to increase the number of these stations. The Government and the District together established four new combined rainfall and river stations; the District alone established eight combined stations and 13 river stations; and the Weather Bureau alone established 10 new rainfall stations. Thus the river stations were increased from 3 to 25 and the rainfall stations from 15 to 37. These are scattered throughout the Miami Valley, and by means of daily observations a close watch is kept on river stages and rainfall. In ordinary weather these observations are transmitted weekly to the district forecaster, but in times of storm or impending flood they are sent in by telephone or telegraph as often as is necessary. The forecaster may have to get up at midnight or at 1 or 2 o'clock in the morning to receive them and, in turn, to arouse the Conservancy engineers and other people whose property may be threatened.

The flood-warning service is as valuable in preventing unnecessary expense and alarm as it is in giving alarm when danger really impends. The memory of the 1913 flood is still fresh in people's minds. On January 31 and March 27, 1916, for instance, when the weather and river conditions seemed ominous, many would have moved out of their houses, farmers would have moved their livestock, construction companies their equipment, and merchants their stocks of goods, if they had not been assured that such steps were unnecessary. On the first of these dates two of the Conservancy engineers devoted their entire time all through the day and following night to answering telephone calls regarding river conditions. Two men of the United States Weather Bureau were also on duty from early morning until late at night answering such calls, which totaled about 1,600 in number. These inquiries came from all parts of the valley, from Piqua on the north to Hamilton on the south. At the same time an engineer experienced in flood fighting was sent to each of the cities where conditions seemed dangerous, to work with the local officials in taking such steps as might be necessary.

An instance of the value of such service in property conservation is the case of the Esterline Co., of Lafayette, Ind. This company had only 4 or 5 hours' notice of the flood in 1913, but in that time it moved from its buildings about $100,000 worth of merchandise, and all of its records, office furniture, and fixtures. The belting was removed from the machinery, which was then heavily coated with grease. By these precautions the company prevented an estimated loss of $60,000.

It is evident that such a service may well be the means of saving life as well as property by warning people who live on low ground to move when dangerous floods impend.

It will be clear from what has been said that the service of the flood-warning bureau is of great value, both to the Conservancy district in its work and to the people of the valley, and that compared with its value it is very inexpensive. A considerable part of this expense, moreover, is borne by the Federal Government.[1]

ADDITIONAL NOTE.

By R. FRANK YOUNG, Meteorologist.

[Dated: Weather Bureau, Dayton, Ohio, Feb. 10, 1919.]

The Miami River at Dayton has not reached the flood stage since the destructive flood of March 25–28, 1913, the nearest approach to flood since the latter date being on January 31, 1916, when it reached a stage of 14.7 feet.

The flood stage at Dayton is 18 feet, but as the levees afford protection to about 5 feet above this there is no real danger to the city till the water rises above 22 feet. It has been the experience of the Weather Bureau office, however, that a period of unusually heavy rains, with a rise to 12 feet or above causes much anxiety among the people living in the lower districts, and this may easily develop into something approaching a panic by the spreading of false rumors as to warnings. The telephone is, of course, an indispensable means of disseminating information at such a time, but in some instances the two telephones in use proved wholly inadequate to meet the

[10] A very comprehensive discussion of the precipitation-altitude relation for the British Isles will be found in a paper by Salter, C. The Relation of Rainfall to Configuration. (London Institution of Water Engineers. 1918, 37 pp., 2 pl.)

[1] See also, W. A. Drake, "The Miami Conservancy Flood Prevention Plan," Sci. Am., Mar. 22, 1919, pp. 282-283, 299-300, 5 figs.